New Developments in Inflationary Cosmology

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NORDITA

Origin

Embedding & Not Inventing

Trustable

Testable

Allahverdi, Enqvist, Garcia-Bellido, Mazumdar, Phys. Rev. Lett. (2006)
Allahverdi, Enqvist, Garcia-Bellido, Jokinen, Mazumdar (2006)

Collaborators

- Rouzbeh Allahverdi
- Bhaskar Dutta
- Kari Enqvist
- Andrew Frey
- Juan Garcia-Bellido
- Asko Jokinen
- Alex Kusenko
- Antonio Masiero

Burden on Inflation

- To provide a successful condition for Big bang
- To create Baryons and Dark Matter

Problems with an absolute Gauge Singlet

Couplings & masses are arbitrary

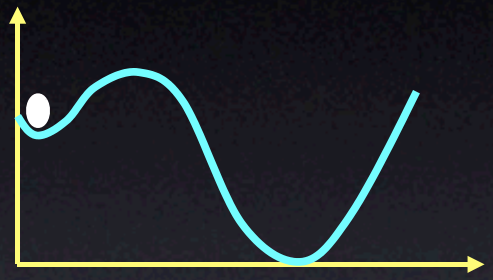
No symmetry argument which prohibits higher order terms with gauge singlets

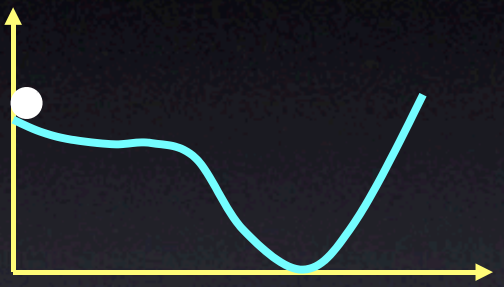
How would one guarantee a successful BBN ?

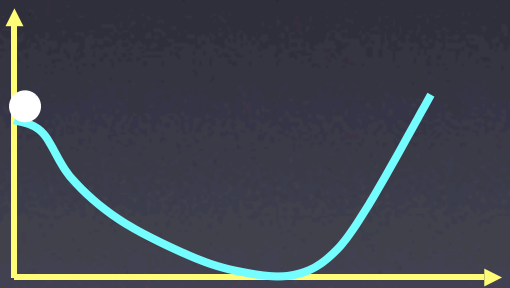
Problem with the Guth's Model

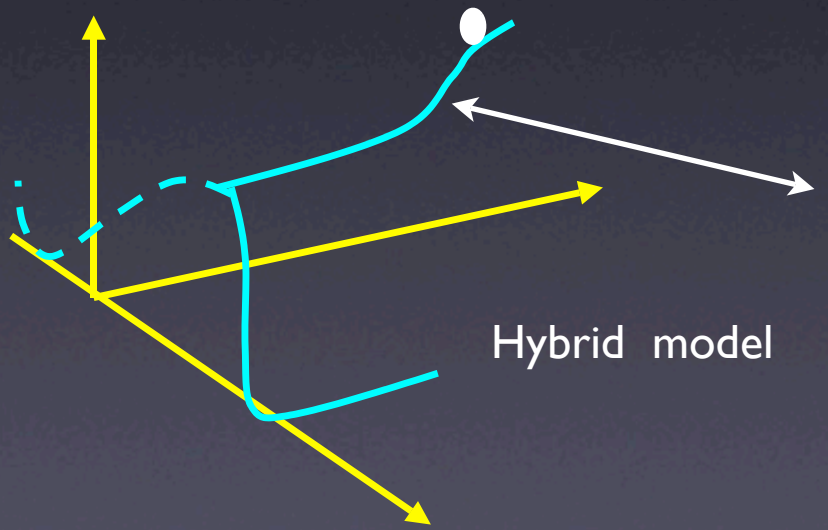
SU(5) Higgs

1) Get rid of the bump (tuning)
2) Flattening the potential
3) Radiative corrections spoil the potential









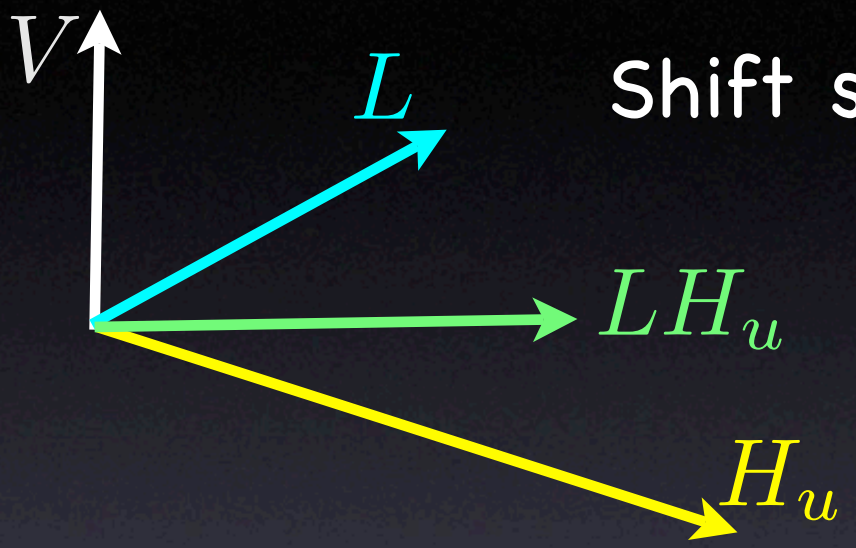
Gauge Singlet

Hybrid model

Stability under R. C. ===> SUPERSYMMETRY

MSSM Flat directions

	B−L	Always lifted by W_{renorm}?
LH_u	−1	
H_uH_d	0	
udd	−1	
LLe	−1	
QdL	−1	
QuH_u	0	√
QdH_d	0	√
LH_de	0	√
QQQL	0	
QuQd	0	
QuLe	0	
uude	0	
$QQQH_d$	1	√
QuH_de	1	√
dddLL	−3	
uuuee	1	
QuQue	1	
QQQQu	1	
$dddLH_d$	−2	√
$uudQdH_u$	−1	√
$(QQQ)_4LLH_u$	−1	√
$(QQQ)_4LH_uH_d$	0	√
$(QQQ)_4H_uH_dH_d$	1	√
$(QQQ)_4LLLe$	−1	
uudQdQd	−1	
$(QQQ)_4LLH_de$	0	√
$(QQQ)_4LH_dH_de$	1	√
$(QQQ)_4H_dH_dH_de$	2	√



Shift symmetry

$$H_u = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ \phi\end{pmatrix},\ L = \frac{1}{\sqrt{2}}\begin{pmatrix}\phi\\ 0\end{pmatrix}$$

$$\Phi = LH_u \equiv c\phi^2$$

$$In\ \ general\ \ \ \Phi = c\phi^m$$

300 such combinations

SUSY is broken

- MSSM is valid below a certain scale

$$W = W_{\rm renorm} + \sum_{n>3} \frac{\lambda}{M^{n-3}} \Phi^n \, .$$

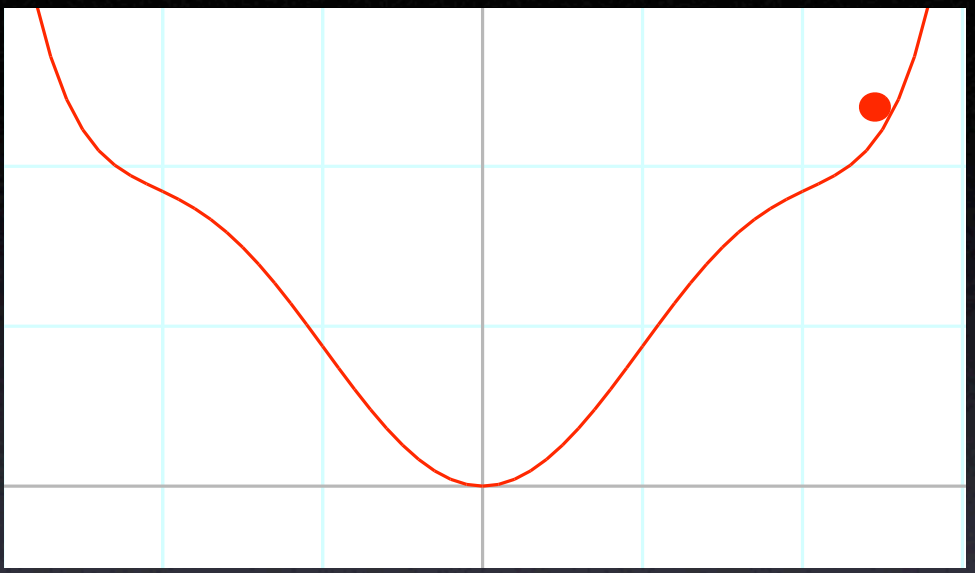
- Soft SUSY breaking mass term
- The Non-renormalizable term
- The A-term

ph/0605035
ph/0608138
ph/0610134

$$V = \frac{1}{2} m_\phi^2 \, \phi^2 + A \cos(n\theta + \theta_A) \frac{\lambda_n \phi^n}{n \, M_{\rm P}^{n-3}} + \lambda_n^2 \frac{\phi^{2(n-1)}}{M_{\rm P}^{2(n-3)}} \, ,$$

$$\cos(n\theta + \theta_A) < 0. \qquad \lambda_n \sim \mathcal{O}(1)$$

2 Possibilities



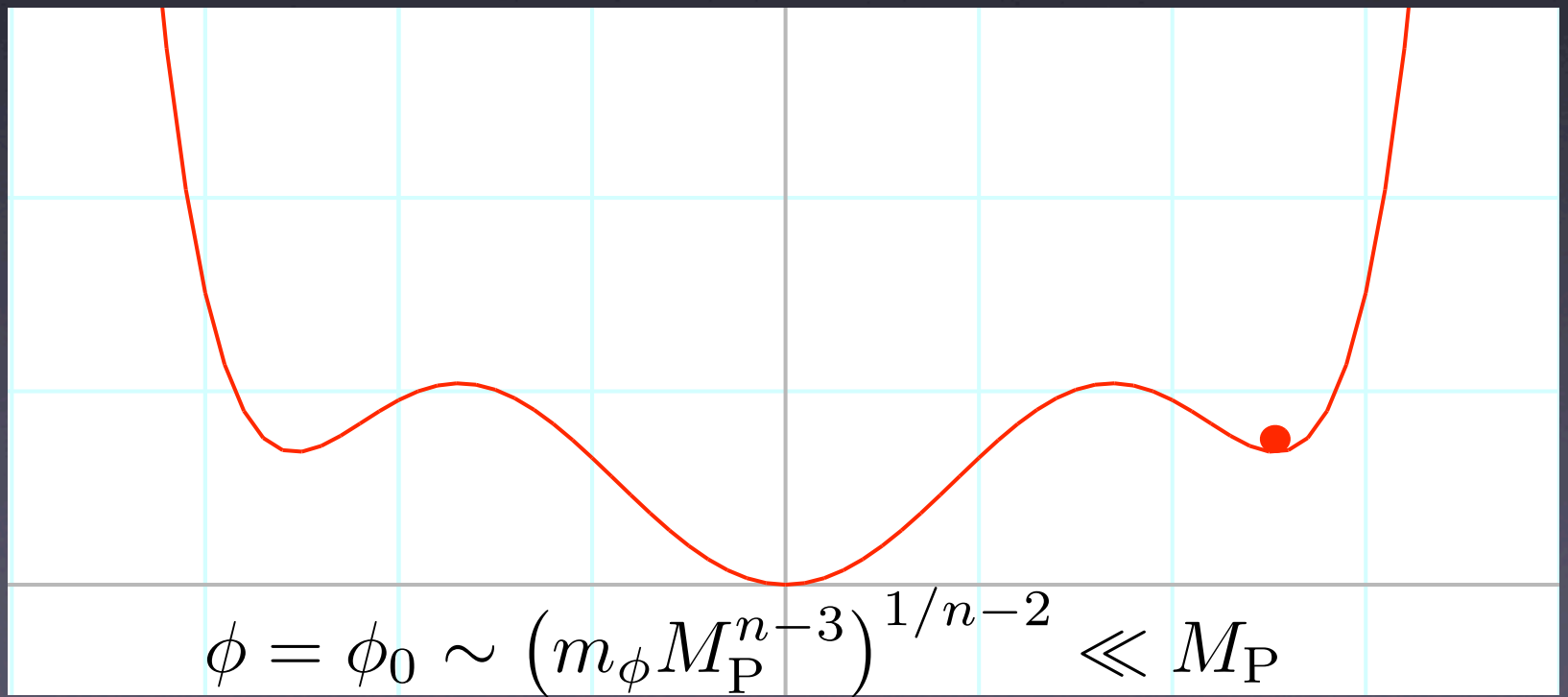
$$A^2 \leq 8(n-1)m_\phi^2$$

Fast roll ==> No Inflation

$$A^2 \geq 8(n-1)m_\phi^2$$

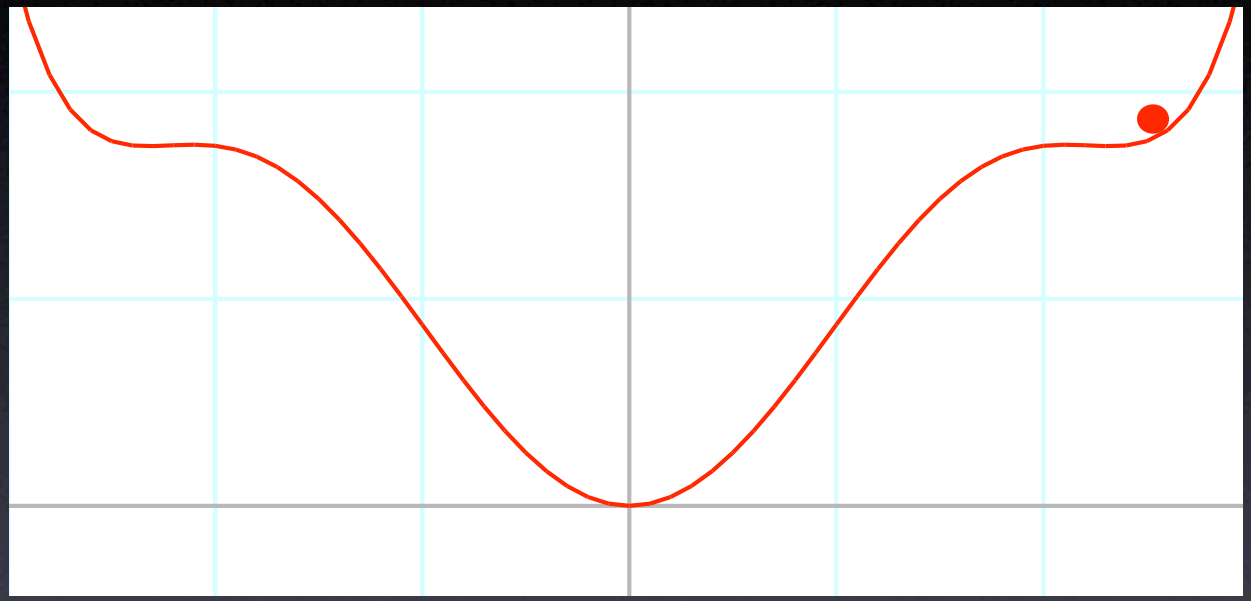
Eternal Inflation

Guth's Problem



Cosmologically Flat Potential

$$m^2_{eff}(\phi_0) \ll H^2_{inf} \longleftrightarrow A^2 = 8(n-1)m^2_\phi$$



$$V'(\phi_0) = 0, \quad V''(\phi_0) = 0$$

$$V'''(\phi_0) \neq 0$$

$$m_\phi \sim 1 \text{ TeV}$$

$$H_{inf} \sim 1 \text{ GeV}$$

$$\phi_0 = 3 \times 10^{14} \; GeV$$

Eternal & Slow Roll Phase of Inflation

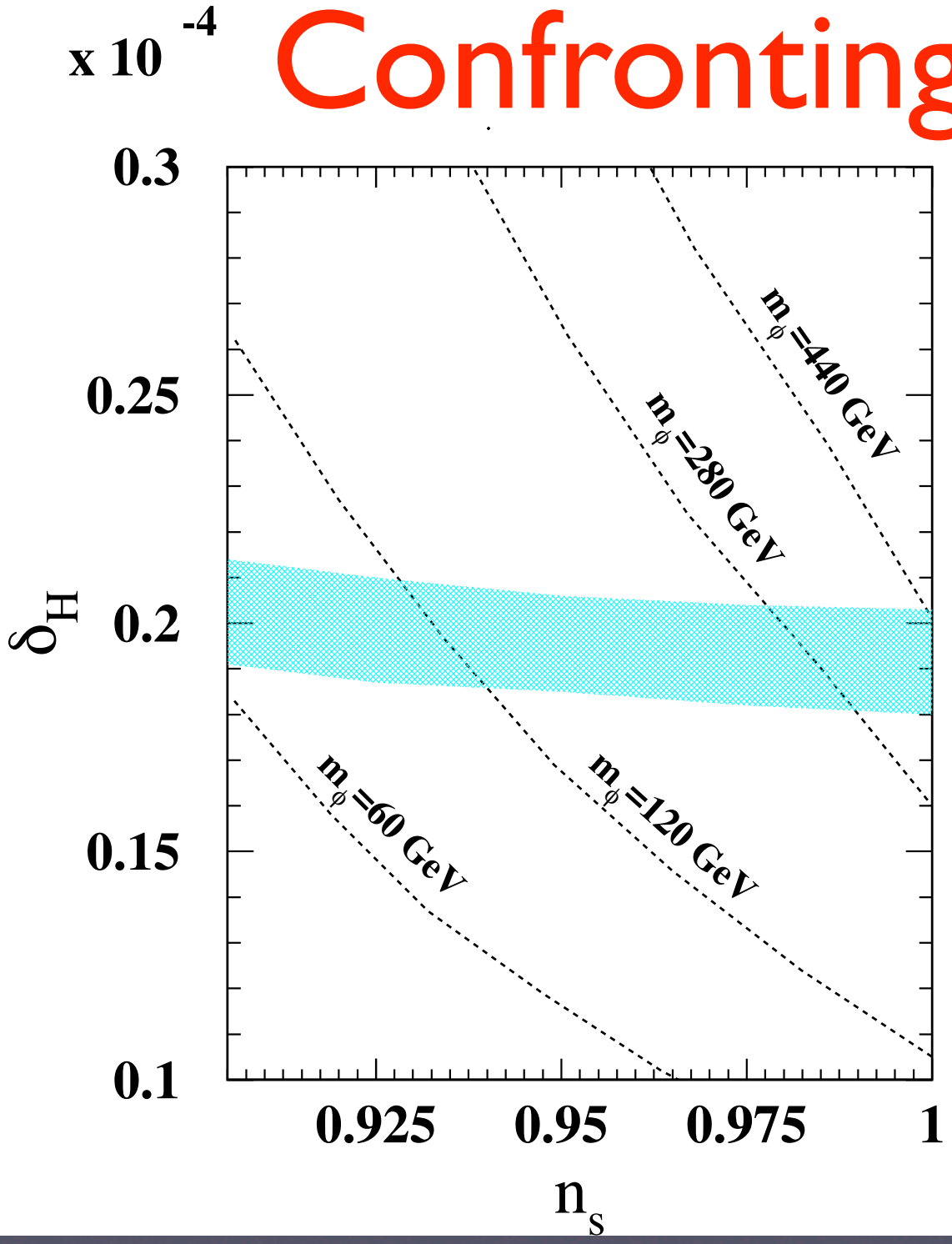
$$\Delta\phi \sim \frac{H^2_{inf}}{V'''(\phi_0)} \sim \left(\frac{\phi_0^3}{M_P^2}\right) \gg H_{inf}$$

Sub-Planckian VeV, No trans-Planckain corrections

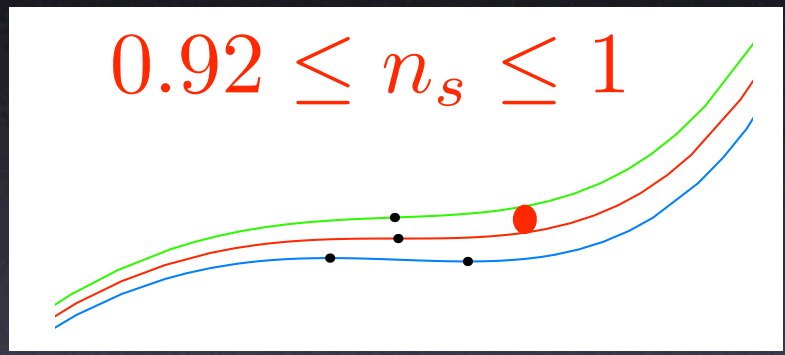
The predictions are robust, i.e. SUGRA corrections are negligible

$$\left(\frac{H_{inf}}{m_\phi}\right)^p \ll 1$$

Confronting the data



- Deviation from the saddle point



Allahverdi, Dutta, Mazumdar, hep-ph/0702112

What are the candidates ?

$$V = \frac{1}{2} m_\phi^2 \phi^2 + A\cos(n\theta+\theta_A)\frac{\lambda_n \phi^n}{n M_{\rm P}^{n-3}} + \lambda_n^2 \frac{\phi^{2(n-1)}}{M_{\rm P}^{2(n-3)}}\,, \qquad W = W_{\rm renorm} + \sum_{n>3} \frac{\lambda}{M^{n-3}}\Phi^n$$

$$u_i^\alpha = \frac{1}{\sqrt{3}}\phi\,,\ d_j^\beta = \frac{1}{\sqrt{3}}\phi\,,\ d_k^\gamma = \frac{1}{\sqrt{3}}\phi\,. \qquad \text{Baryonic}$$

$$L_i^a = \frac{1}{\sqrt{3}}\begin{pmatrix} 0 \\ \phi \end{pmatrix}\,,\ L_j^b = \frac{1}{\sqrt{3}}\begin{pmatrix} \phi \\ 0 \end{pmatrix}\,,\ e_k = \frac{1}{\sqrt{3}}\phi\,, \qquad \text{Leptonic}$$

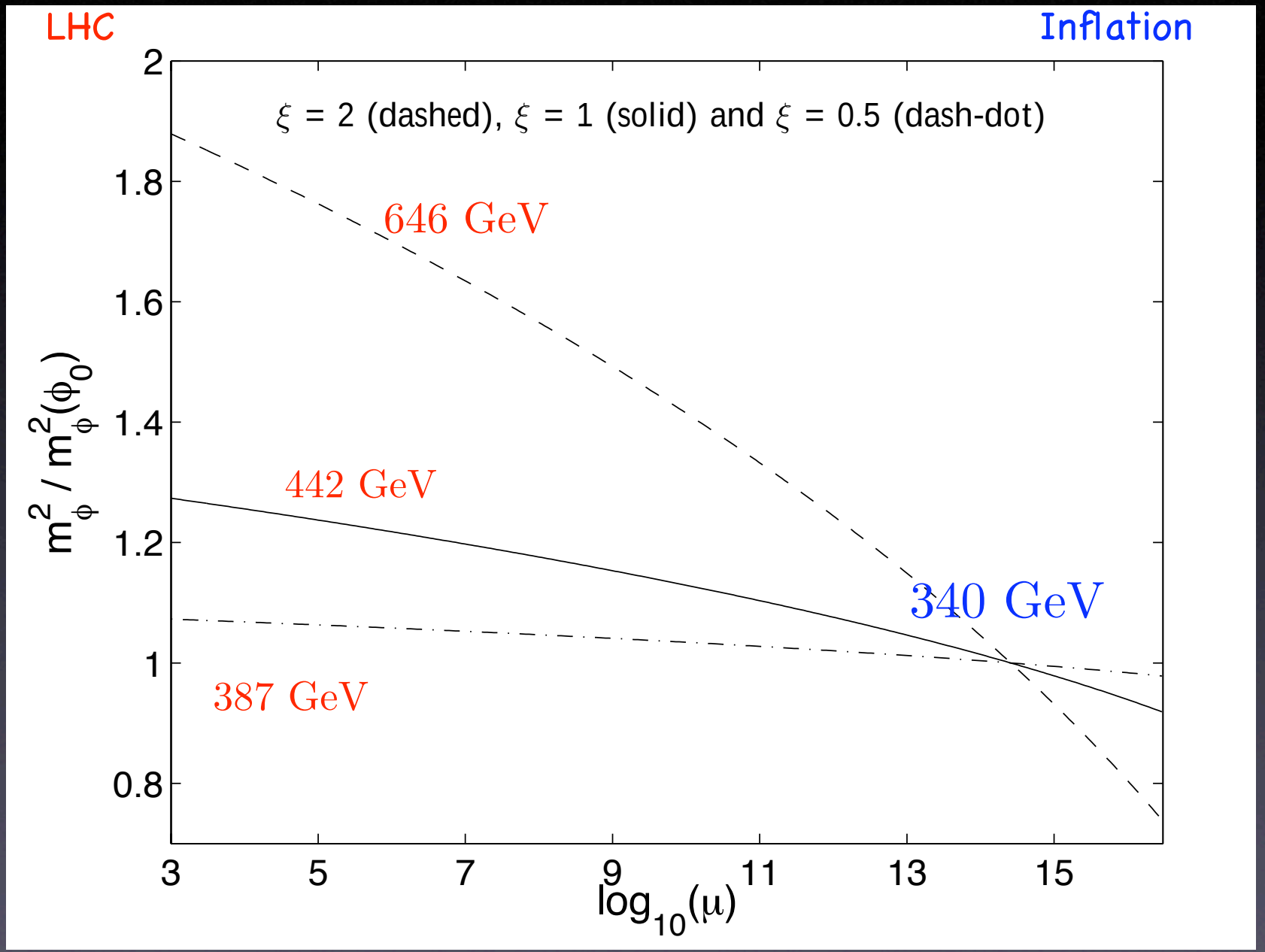
Both the directions are lifted by themselves

$$W_6 \supset \frac{1}{M_{\rm P}^3}(LLe)(LLe)\,, \qquad W_6 \supset \frac{1}{M_{\rm P}^3}(udd)(udd)$$

$$m_\phi \sim 1TeV,\quad n = 6,\quad A = \sqrt{40} m_\phi$$

$$\lambda_n \sim 1 \to SU(5),\quad \sim 0.01 \to SO(10)$$

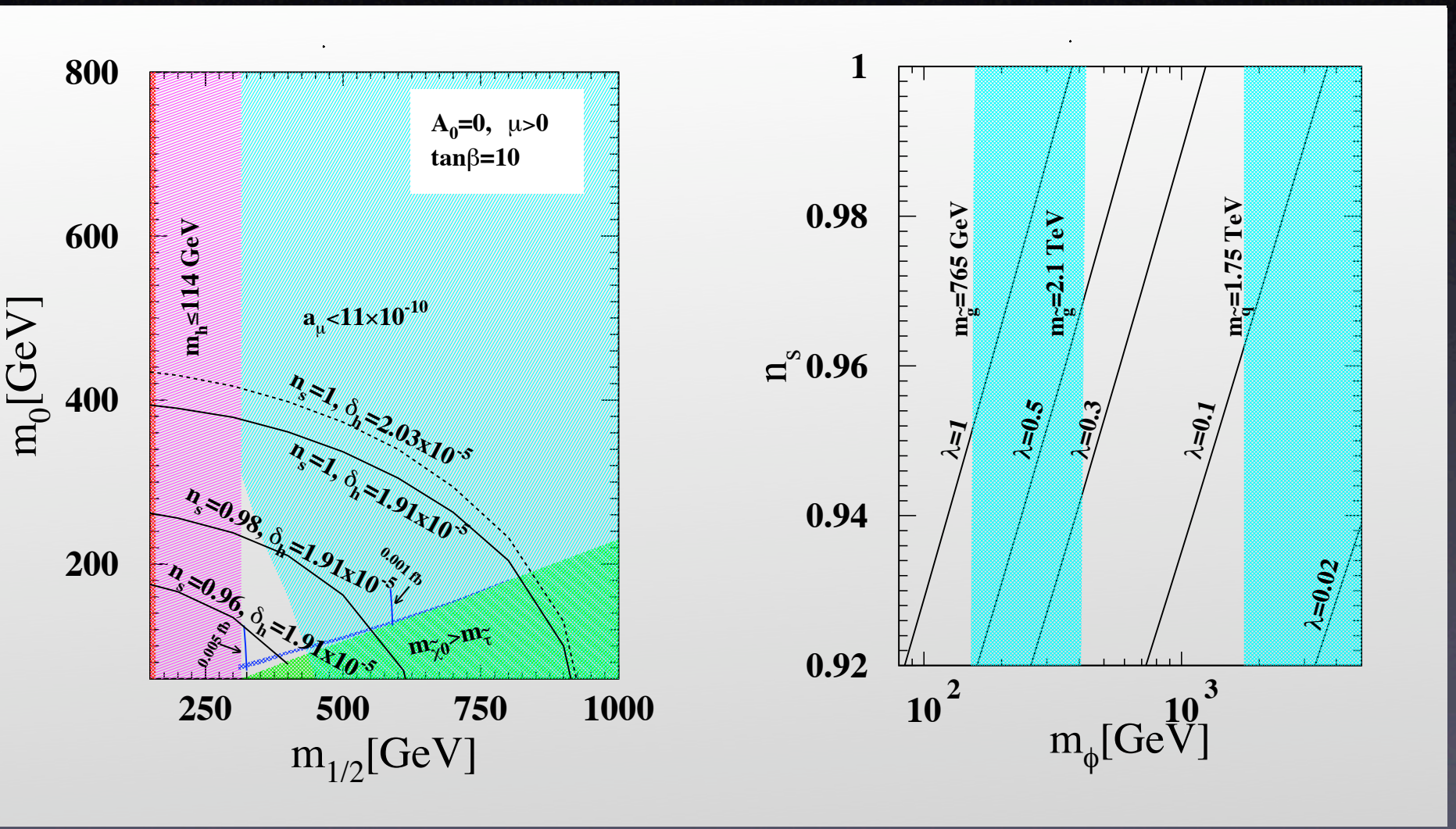
Inflation & LHC



Allahverdi, Enqvist, Garcia-Bellido, Jokinen, Mazumdar (2006)

CDM, Inflation & LHC

- If MSSM is the correct description of nature then it must provide answers to Inflation & DM with an overlapping parameter region



Allahverdi, Dutta, Mazumdar, hep-ph/0702112

Embedding MSSM inflation within GUT

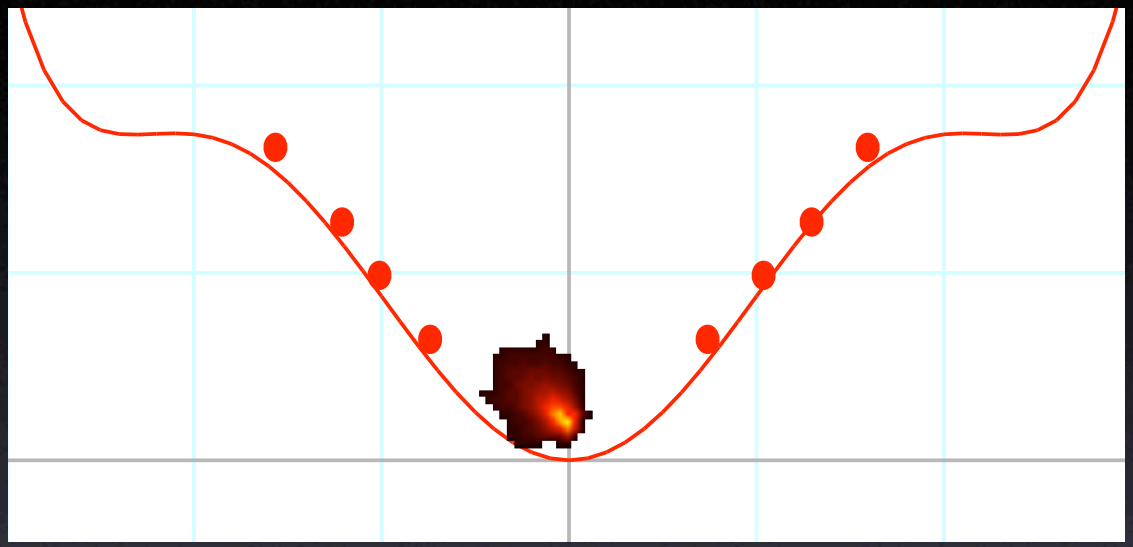
$$W \supset \frac{NLLe}{M_{GUT}} \qquad W \supset \frac{Nudd}{M_{GUT}}$$

- Right handed Neutrino lifts the LLe direction before n=6, but udd survives till n=6
- udd has more D-terms than LLe

udd is the Inflaton: A baryon, SUSY partner of the Neutron

Allahverdi, Dutta, Mazumdar, hep-ph/0702112

After Inflation



$$T_{rh} \sim 10^4 GeV$$

- The flat direction Couplings are well known: SM Yukawas and Gauge interactions
- Flat direction VEV breaks part of SM gauge group
- Baryon dissociates into HEAVY Gluons/Gluinos and Fermion/Sfermion
- Thermalization is complete when the flat direction evaporates completely.

Allahverdi, Enqvist, Garcia-Bellido, Jokkinen, Mazumdar, (2007)

Challenges & Future prospects

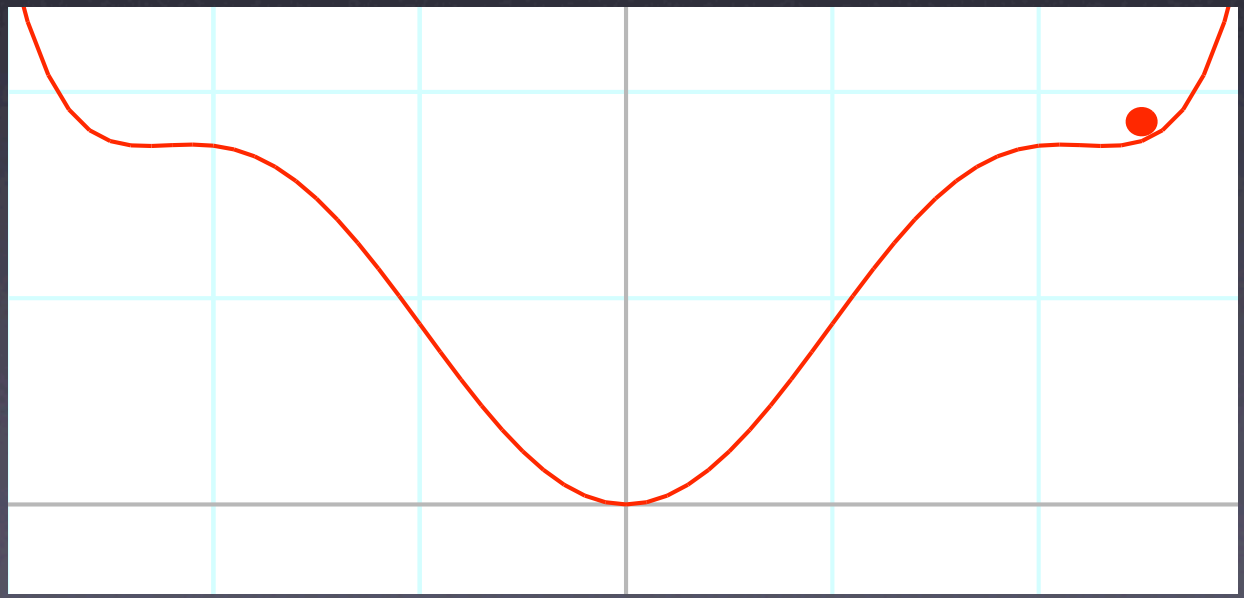
- How to maintain the potential flat ?

SUSY helps, nevertheless one requires fine tuning

Allahverdi, Enqvist, Garcia-Bellido, Mazumdar, Phys. Rev. Lett. (2006)
Allahverdi, Enqvist, Garcia-Bellido, Jokinen, Mazumdar (2006)

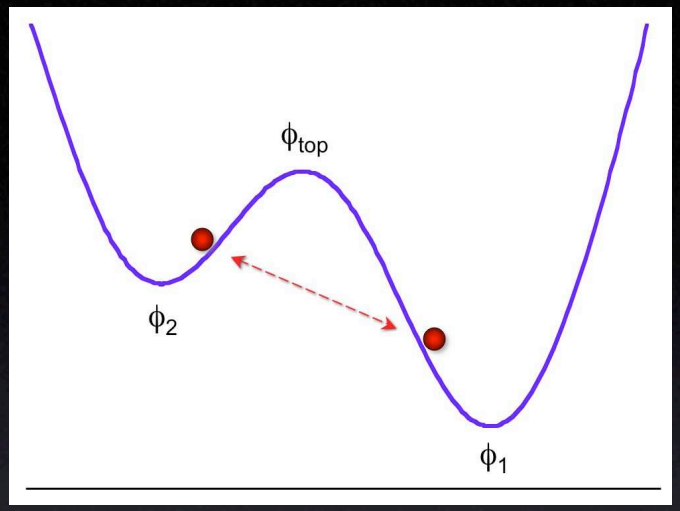
- How to start at the flat part of the potential ?

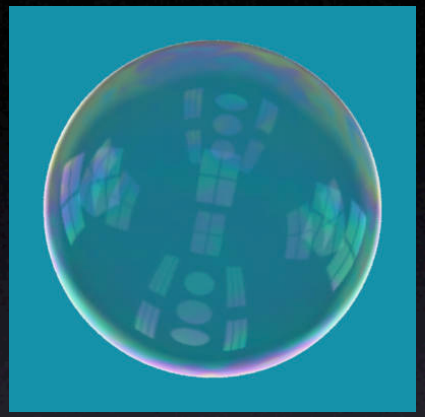
Needs high scale inflation, i.e.
String Landscape

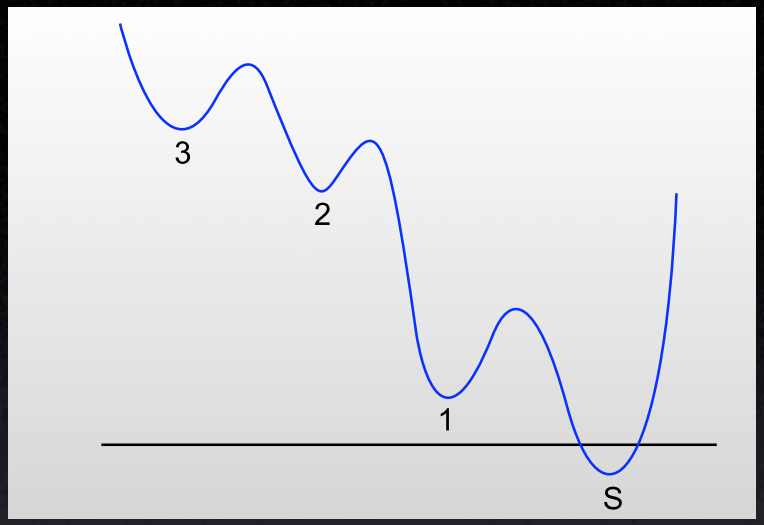


Allahverdi, Frey, Mazumdar (2007)

Addressing the initial condition problem ?







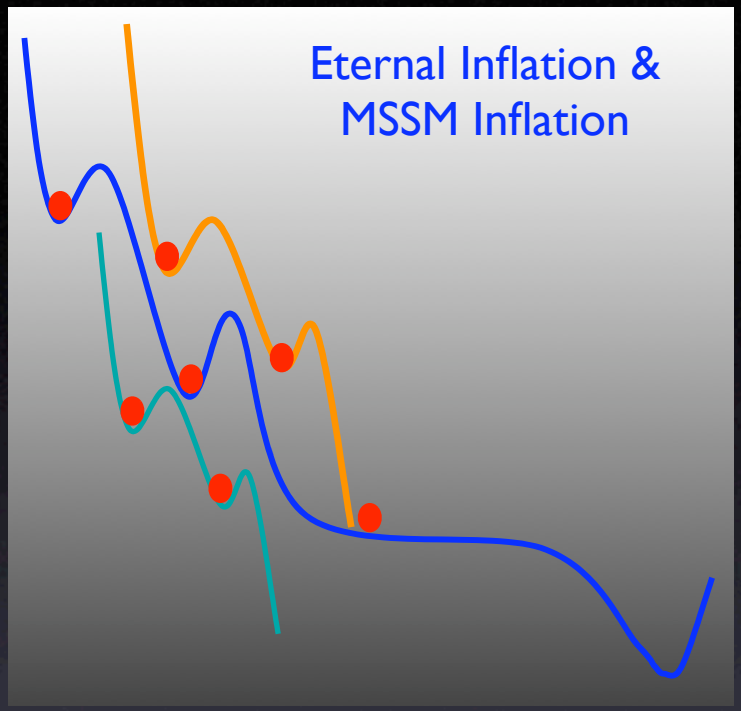
Guths' model of inflation

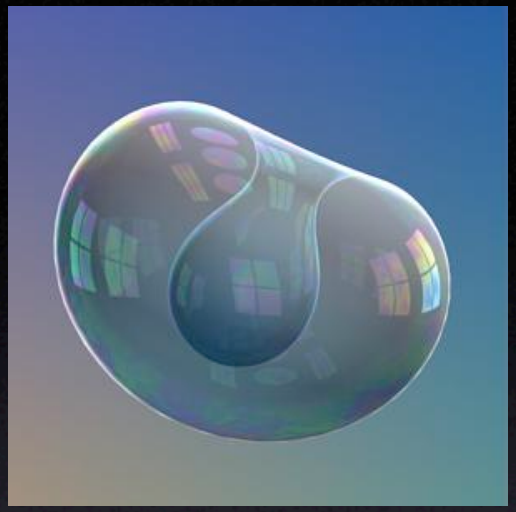
Multiverse due to landscape

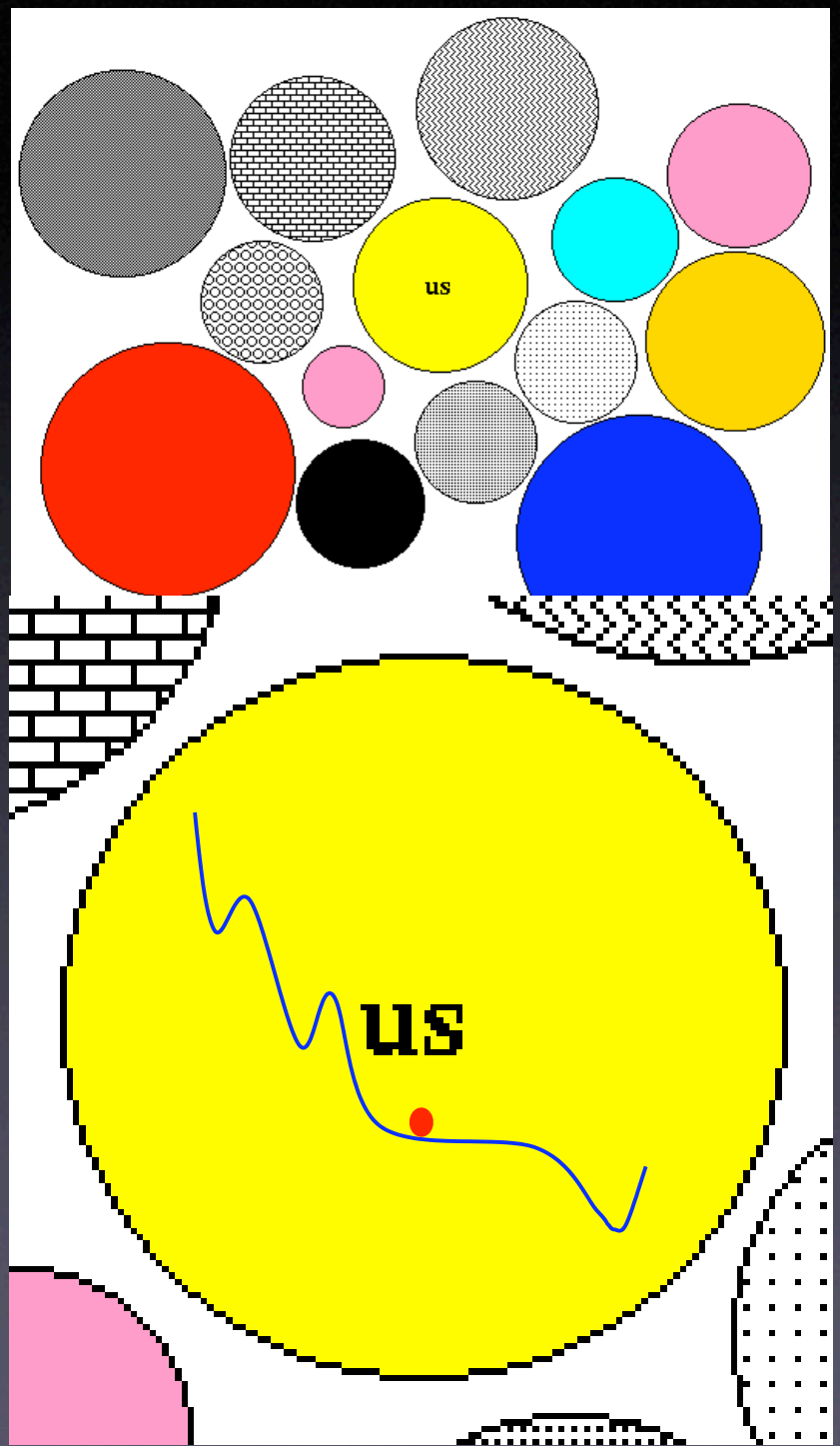
- Phenomenologically incomplete
- String theory provides multiple vacua $\sim 10^{500} - 10^{1000}$
- Multiple vacua leads to eternal inflation

Allahverdi, Frey, Mazumdar (2007)

Eternal Inflation ending in MSSM vaccum







- Universe starts at a string scale
- The final stage of inflation is driven by MSSM inflation

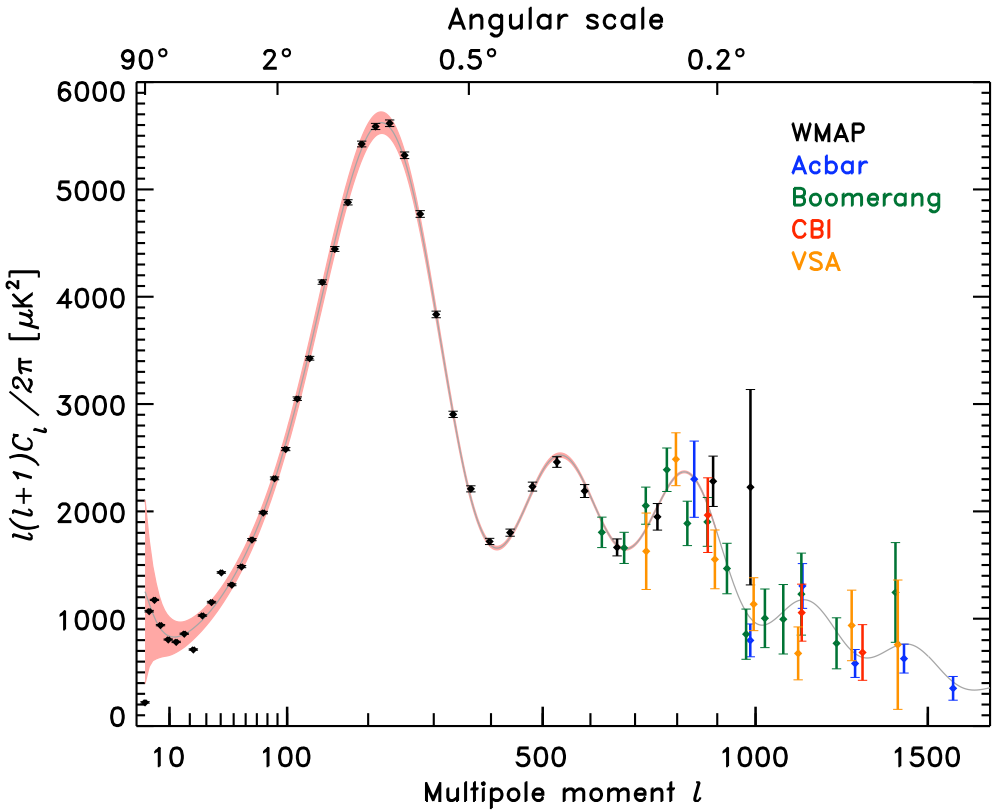
Allahverdi, Frey, Mazumdar (2007)

Message & Conclusion

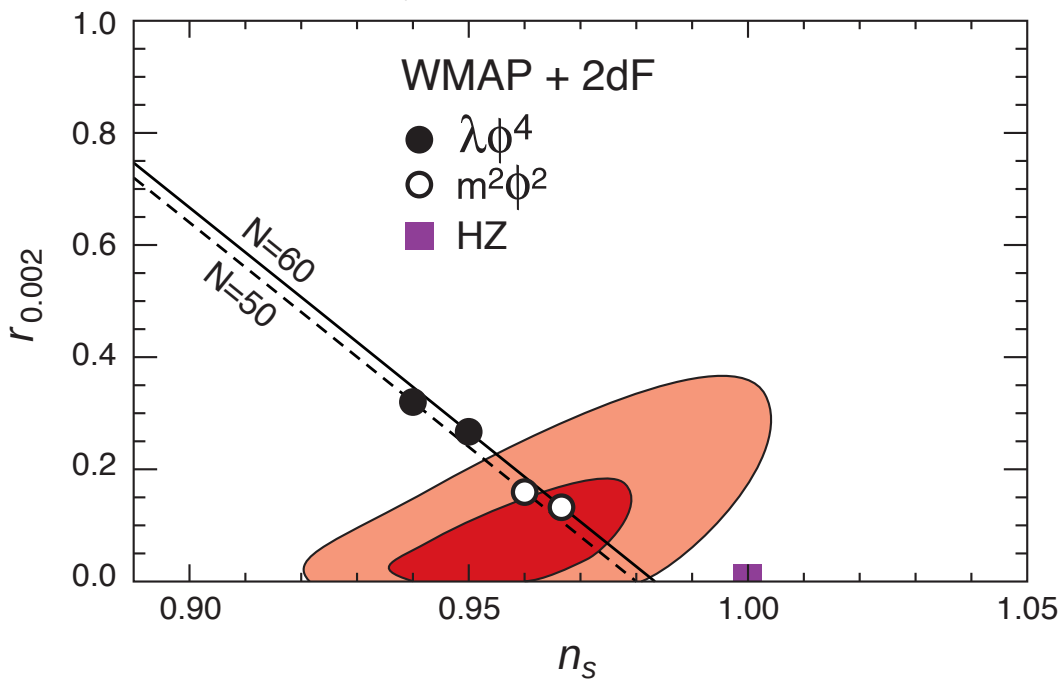
- Physics is more enjoyable without absolute Gauge Singlets

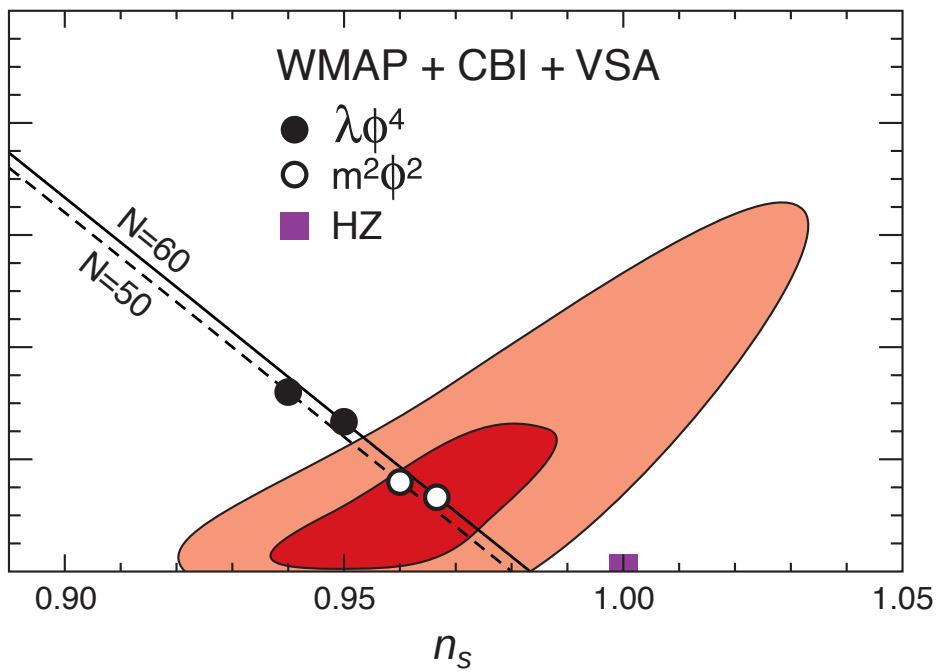
In order to understand the observable Universe the Weak Scale Physics is sufficient !!

CMB data



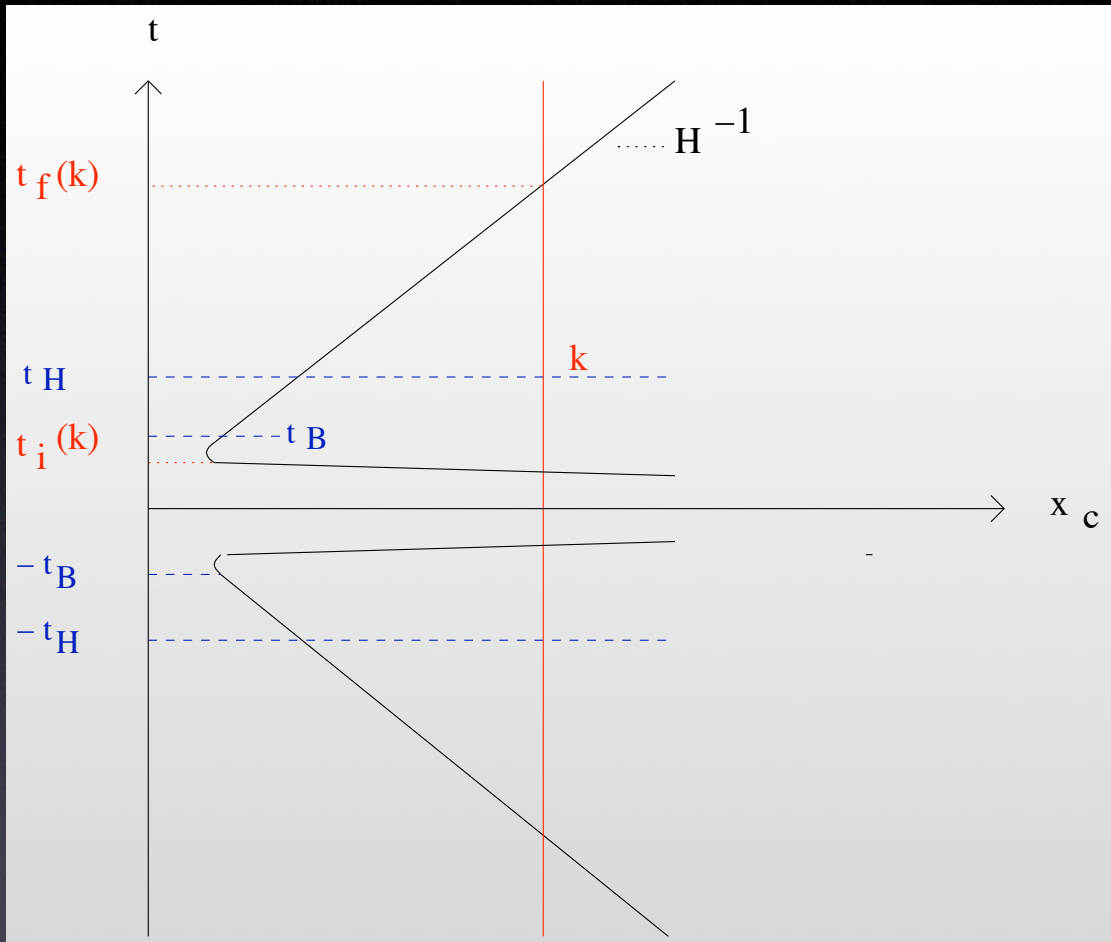
$$\left\langle \frac{\delta T}{T}, \frac{\delta T}{T} \right\rangle \sim \delta_H^2 \; k^{(n_s-1)}$$

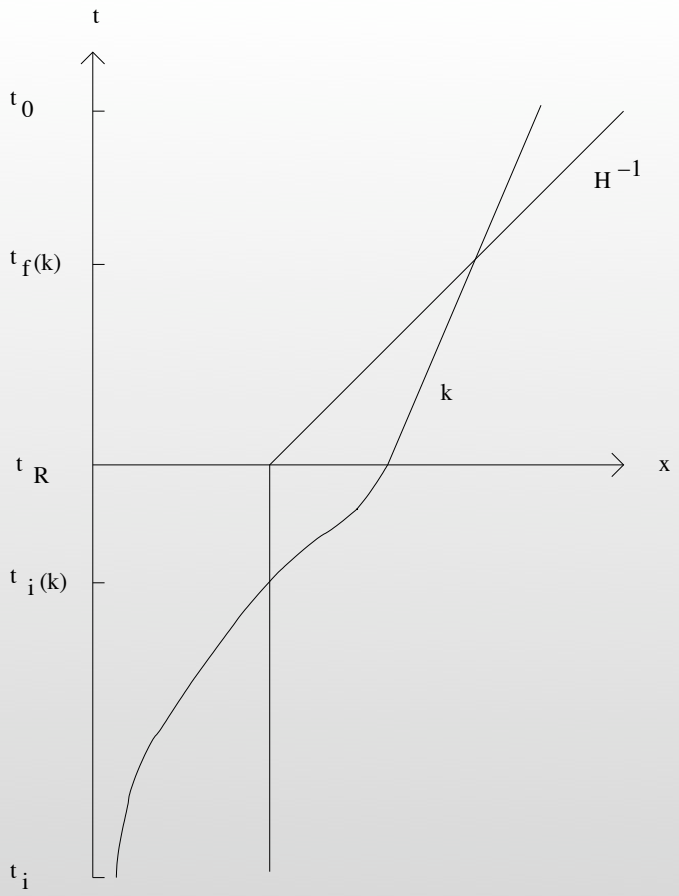




WMAP analysis (2006)

Two Dynamical Possibilities





Bouncing Cosmology

Inflation

Biswas, Brandenberger, Mazumdar, Sigel (2006) ==> Gravity being Ghost and Asymptotically free

- Perturbations are Outside The Hubble Patch